

QCD AT HIGH-LUMINOSITY HADRON COLLIDERS ^a

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This talk gives a brief introduction to open questions in jet physics and QCD which come to the fore in the high-luminosity regime characterizing the upcoming phase of the Large Hadron Collider and future hadron colliders.

Precision studies of the Standard Model (SM) and searches for rare processes beyond the SM in experiments at the Large Hadron Collider (LHC) rely on the reduction of statistical errors which will be achieved by the increase in luminosity at the LHC Run II and further boosted by the high-luminosity upgrade foreseen for 2020.

For large luminosity, kinematic regions characterized by small event rates can be explored, while new experimental challenges are posed by “pile-up”, i.e., the high number of overlaid proton-proton collisions.

The focus of this article is on QCD theoretical issues arising in regions accessible at high luminosity, and open questions in handling high pile-up, in particular regarding the treatment of QCD jet correlations.

Consider the class of processes depicted in Fig. 1, where massive states such as Drell-Yan lepton pairs, heavy flavor pairs, Higgs bosons, or new beyond-Standard-Model (BSM) states are produced in association with jets. LHC kinematics is characterized by a very wide range in rapidity which can be covered by detectors and where interesting physics signals can appear, and by a very large range in the ratios of the energy scales S , s_{jj} , and s_H in Fig. 1.

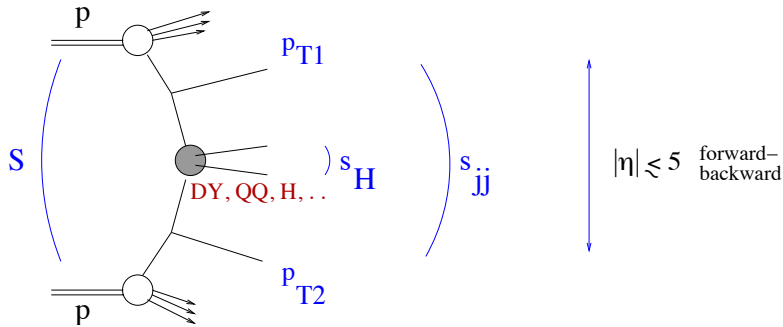


Figure 1 – Production of heavy-mass states (Drell-Yan lepton pairs, heavy flavor pairs, Higgs bosons, new BSM states) in association with jets at the LHC.

The exclusive phase space boundary region $s_H/S \rightarrow 1$ can be accessed with high luminosity, and will be relevant to searches for high-mass BSM states as well as SM studies such as high-mass $t\bar{t}$ and Drell-Yan production. This is a region where color radiation is strongly suppressed.

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Reliable theoretical predictions will require QCD calculations to take into account infrared gluon effects from the imbalance between virtual processes and real emission to all orders in α_s , and model nonperturbative color flow and color reconnection effects. Besides the partonic channels, initial-state color-singlet channels become non-negligible near the exclusive phase space boundary. An example is photon-photon production, whose impact on BSM heavy neutral Z' -boson searches is analyzed in Refs^{1,2}.

The region $s_{jj} \approx S$, with $s_{jj} \gg s_H \gg \Lambda_{\text{QCD}}$, is also relevant to studies of new physics effects at the highest energy scales. Because of the large dijet sub-energy this region probes the dynamics of structure functions and parton cascades near the kinematic limit $x \rightarrow 1$ ³. However, since $s_H/s_{jj} \ll 1$, the phase space opens up for finite-angle, multi-gluon radiation associated with scattering in the high-energy limit⁴. The interplay of these effects has never been investigated before and will be explored in high-luminosity experiments.

Analyses performed at Run I have already pointed to the importance of dijet distributions for increasing dijet masses — see e.g. the comparison in Fig. 2⁵ of dijet mass measurements in W -boson + jets production with the next-to-leading-order (NLO) calculation matched to parton shower BLACKHAT + SHERPA⁶ for masses in the region above 500 GeV. Similar effects are seen in Fig. 2 from the comparison with the ALPGEN⁷ Monte Carlo. See Ref.⁸ for discussion of mass distributions in the context of transverse-momentum dependent (TMD) approaches to parton cascades' evolution, which go beyond the NLO+shower approach^b by incorporating kinematical corrections due to energy-momentum conservation constraints¹¹ and dynamical contributions due to finite-angle multi-gluon radiation¹². See Ref.¹³ for related comparisons of vector boson transverse momentum p_T measurements in Z -boson + jets production at Run I with MADGRAPH¹⁴ and SHERPA¹⁵ Monte Carlo calculations in the region of p_T of several hundred GeV.

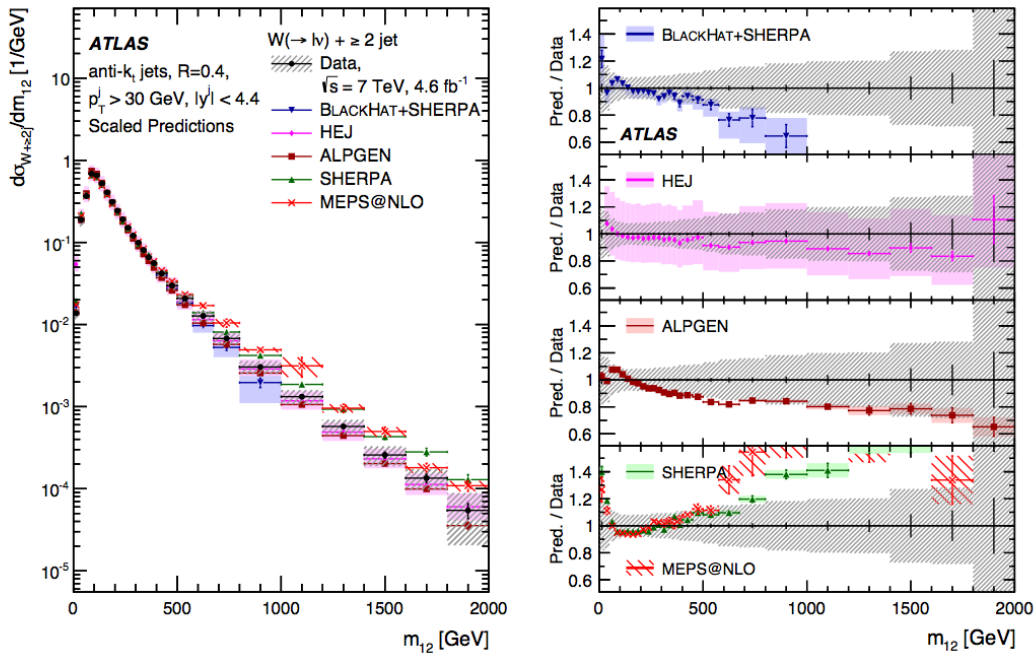


Figure 2 – Di-jet invariant mass measured⁵ in LHC final states with W -boson + 2 jets, compared with parton-shower Monte Carlo calculations.

With increasing luminosity, measurements of processes such as those in Fig. 1 face the challenge of pile-up, which reaches the level of 50 proton-proton collisions per bunch crossing at

^bIf TMD contributions are non-negligible for large jet masses, then extensions of parton distributions as e.g. in Refs⁹ are likely to become relevant, particularly in the forward region¹⁰.

Run II, and will be higher in higher-luminosity runs^{16–26}. This is especially severe in regions outside tracker acceptances, where techniques based on precise vertex and track reconstruction are not available.

Different effects of pile-up in Z -boson + jets production are discussed in Ref.²⁷. The discussion can be extended to other processes in Fig. 1. One effect consists of additional pile-up particles in the jet cone, leading to a jet pedestal. Another is the overlapping of soft particles from pile-up, which are clustered into jets. A further effect is the mistagging of high transverse momentum jets produced from independent pile-up events. Several methods exist to take the first two effects into account and correct for them. These include techniques based on the jet vertex fraction¹⁸ and charged hadron subtraction^{20,28}, the PUPPI method²⁹, the SoftKiller method³⁰, the jet cleansing method³¹. It is pointed out in Ref.³² that the third effect is significant especially in correlation variables and can be treated using a jet mixing method.

Fig. 3³² illustrates an example of Z -boson / jet correlation, showing the Z -boson p_T spectrum in Z + jet production. On the left one sees the result at zero pile-up (solid black curve), the result for $N_{PU} = 50$ pile-up collisions (dot-dashed black), and the result of applying the pile-up removal method SoftKiller³⁰ (dashed blue); on the right is the result of applying the jet mixing method³² (solid red). The main observation is that while methods designed to take into account jet pedestal and soft particles from pile-up work well at the level of leading jet spectra, at the level of correlations the effects left over after soft particle removal are non-negligible, and for these one needs additional methods, of which the jet mixing approach provides an example.

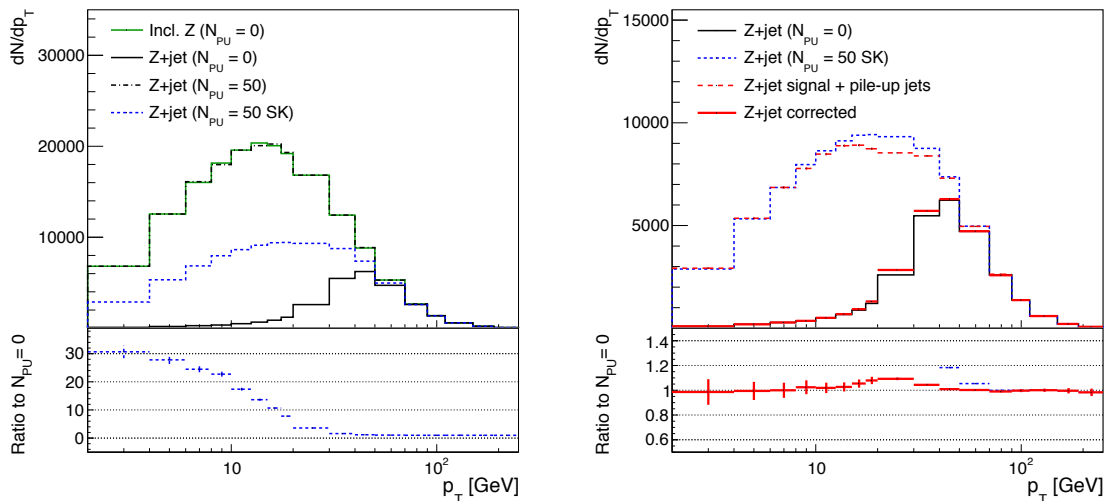


Figure 3 – Effects of pile-up (with number of pile-up collisions $N_{PU} = 50$) on the Z -boson p_T spectrum in Z + jet production³²: (left) application of the pile-up removal method SoftKiller³⁰; (right) application of the jet mixing method³².

It is worth noting that the proposed jet mixing is a statistical method which is data driven, and avoids dependence on Monte Carlo modeling. It also has the distinctive feature of not requiring low pile-up runs but rather making use of experimental data recorded at high pile-up, thus entailing no loss in luminosity²⁷.

We finally observe that the Run II Higgs-boson experimental program is closely linked to aspects of QCD discussed above. In particular, as high statistics is reached in Higgs boson production measurements, a new program of precision studies in gluon fusion at high mass scales becomes possible³³, in which the Higgs boson may be used as a color-singlet pointlike source (in the heavy top quark limit) which couples to gluons, and compared with electroweak sources coupled to quarks, e.g. Drell-Yan production in a comparable mass range. With this, one will be able to access for the first time strong-interaction effects such as color correlations, polarized gluons in unpolarized beams, gluon fusion processes with double spin flip^{8,33}.

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